Towards Consistent Dark Energy Constraints from High- and Low-Redshift Probes with the Extended AP Test

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Outline

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ΛCDM and Its Tensions

- ΛCDM — cosmological constant + cold dark matter — fits most observations well, yet persistent discrepancies motivate extensions
- **Hubble tension:** $H_0^{\rm SH0ES} \approx 73\,{\rm km\,s^{-1}\,Mpc^{-1}}$ vs $H_0^{\rm Planck} \approx 67\,{\rm km\,s^{-1}\,Mpc^{-1}}$
- **Evolving dark energy:** DESI DR2 + Planck + Pantheon+ prefer $w_0 > -1$, $w_a < 0$ at $\gtrsim 3\sigma$
- S_8 **tension:** weak-lensing surveys favour lower clustering amplitude than CMB-inferred ΛCDM
- These tensions point to **different cosmic epochs**: $H_0 \Rightarrow$ pre-recombination; $(w_0, w_a) \Rightarrow$ late-time expansion history; $S_8 \Rightarrow$ late-time growth
- **This talk:** test the evolving-DE signal against an additional low-z probe and early-universe physics

Evidence for Evolving Dark Energy and Phantom crossing

- DESI DR2 + Planck + Pantheon+: $w_0 = -0.838 \pm 0.055$, $w_a = -0.62^{+0.22}_{-0.19}$
  — ΛCDM at $(w_0, w_a) = (-1, 0)$ excluded at $\gtrsim 3\sigma$ [DESI 2025]
- Best-fit CPL implies $w < -1$ at low z (phantom crossing)
- But how robust is this signal?
  - **Dataset dependence:** significance varies with SN catalogue choice

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- But how robust is this signal?
  - **Dataset dependence:** significance varies with SN catalogue choice
  - **Early-universe dependence:** standard BAO relies on r_d — shifts in pre-recombination physics (e.g. EDE) directly bias DE constraints
- **This work:** extend $w^{\rm CPL}$CDM with axion-like EDE and add an r_d-independent low-z anchor (SDSS eAP) — can high-z and low-z probes be made consistent?

Outline

Dark Energy Models

- **Dynamical Dark Energy (CPL):**

$$w(z) = w_0 + w_a(1 - a)$$

Parameters: w_0, w_a. Affects: $H(z)$ and $D_A(z)$
$\Rightarrow$ shifts distance moduli (SN), BAO ratios, AP distortion

- **Early Dark Energy (EDE) — axion potential:**

$$V(\theta) = m^2 f^2 \left[1 - \cos(\theta)\right]^n$$

Parameters: $f_{\rm EDE}$, z_c, $\theta \equiv \phi/f$, n.
Active around pre-recombination, temporarily boosts $H(z)$ before last scattering
$\Rightarrow$ **reduces** r_d, **raises** CMB-inferred H_0
$\Rightarrow$ **no direct late-time imprint** — negligible by $z \sim 10$

Outline

Observational Probes

Probe	Redshift	Parameters
High-z probe:		
Planck – CMB TTTEEE + lensing	$z \sim 1100$	$\omega_{\rm cdm}$, ω_b, $\tau_{\rm reio}$, θ_*, A_s, n_s, $f_{\rm EDE}$, (w_0, w_a weakly)
Low-z probes:		
PantheonPlus – SN Ia	$0.001 < z < 2.26$	Ω_m, w_0, w_a
SH0ES		H_0
SDSS – extended AP	$0.025 < z < 0.7$	Ω_m, w_0, w_a (r_d-independent)
DESI DR2 – BAO	$0.1 < z < 4.2$	Ω_m, H_0, w_0, w_a ($+\omega_b$, $f_{\rm EDE}$ via r_d)

Alcock-Paczynski (AP) test

- An intrinsically isotropic feature appears isotropic **only if** the assumed cosmology is correct
- A wrong cosmology stretches radial and transverse separations by **different factors**:
  - Radial: $s_{\parallel} = c\Delta z/H(z)$ — depends on $H(z)$
  - Transverse: $s_{\perp} = (1+z)\, D_A(z)\, \Delta\theta$ — depends on $D_A(z)$
- Mismatch between the two distortions squashes a circle into an apparent ellipse $\rightarrow$ **the signal**
- The test is r_d-**independent**: the absolute scale cancels in the shape ratio; only the *anisotropy* matters
- Constrained parameters: Ω_m, w_0, w_a

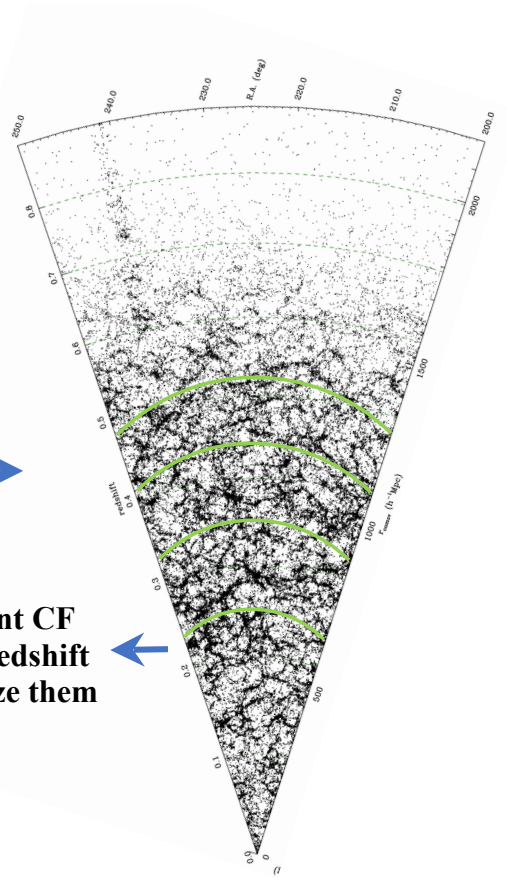
The Extended Alcock-Paczynski Test

using $\xi(s_\perp, s_\parallel)$ as the standard 'shape'

Observed RA, DEC & redshifts of galaxies

Adopt a cosmology, i.e. r(z) relation

Calculated r, θ, ϕ of galaxies



Measure two-point CF $\xi(s_\perp, s_\parallel)$ in each redshift shells & normalize them

Shape differences across redshift shells

$$\Delta\widehat{\xi}(z_i, z_{\rm ref}) = \widehat{\xi}(z_i) - \widehat{\xi}(z_{\rm ref}) - \Delta\widehat{\xi}^{\rm sys}(z_i, z_{\rm ref})$$

Likelihood for many cosmological models

$$\chi^2_{z_{\rm ref}}(\Omega_m, w) = \sum_{\ell=0,2,4} \sum_{\alpha,\beta} P_\ell^{z_{\rm ref}}(s_\alpha) \cdot (C^\ell_{\alpha\beta})^{-1} \cdot P_\ell^{z_{\rm ref}}(s_\beta)$$

Note!

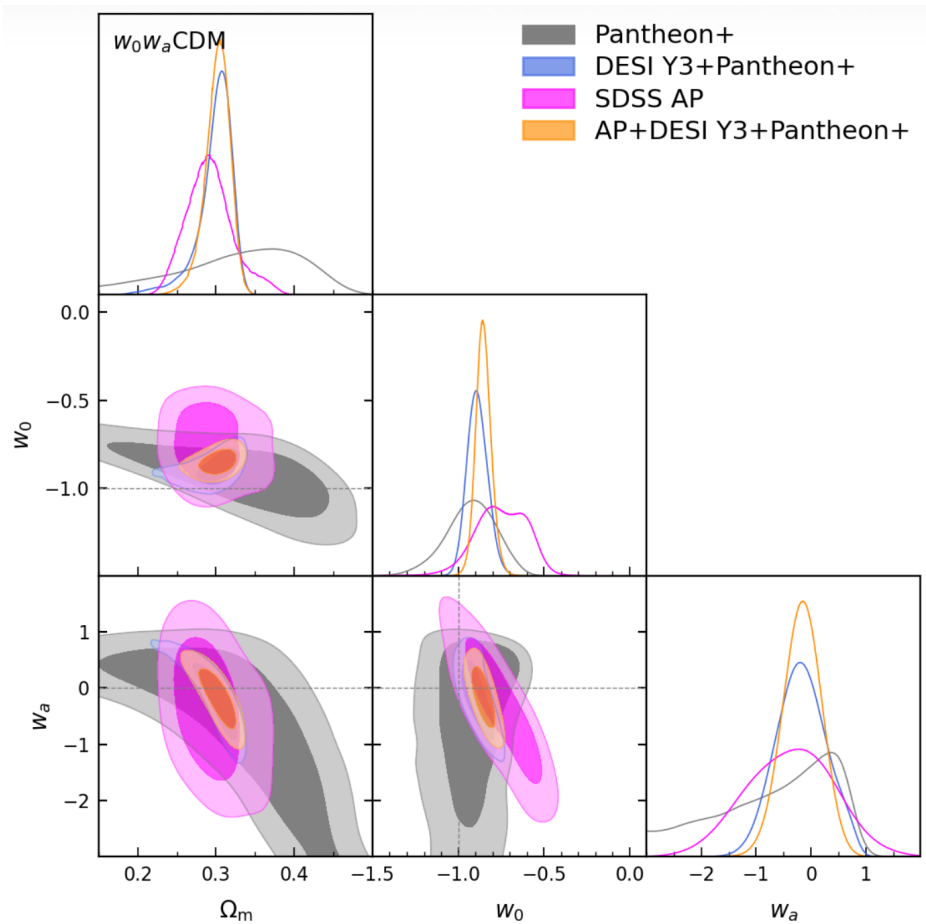
We don't need to know absolute size or shape. Only shape conservation is used across redshifts!

- **Purely geometrical & ~independent of size, mass & clustering evolution!**
- **High statistics!**

see Park et al. (2019), Dong et al. (2023), Dong & Park (2026)

Extended AP test

Low-z constraints from the eAP method paper:

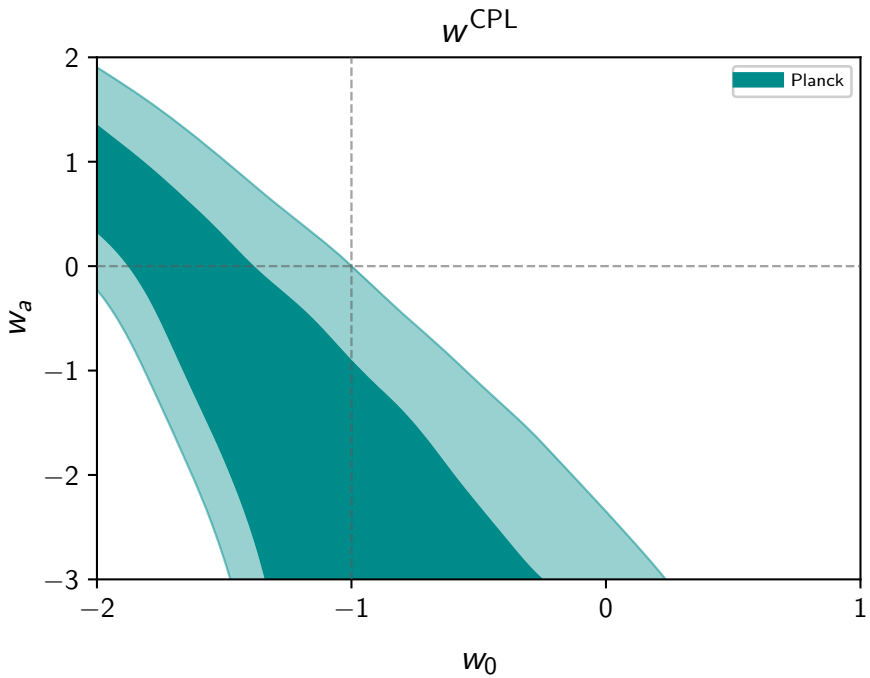


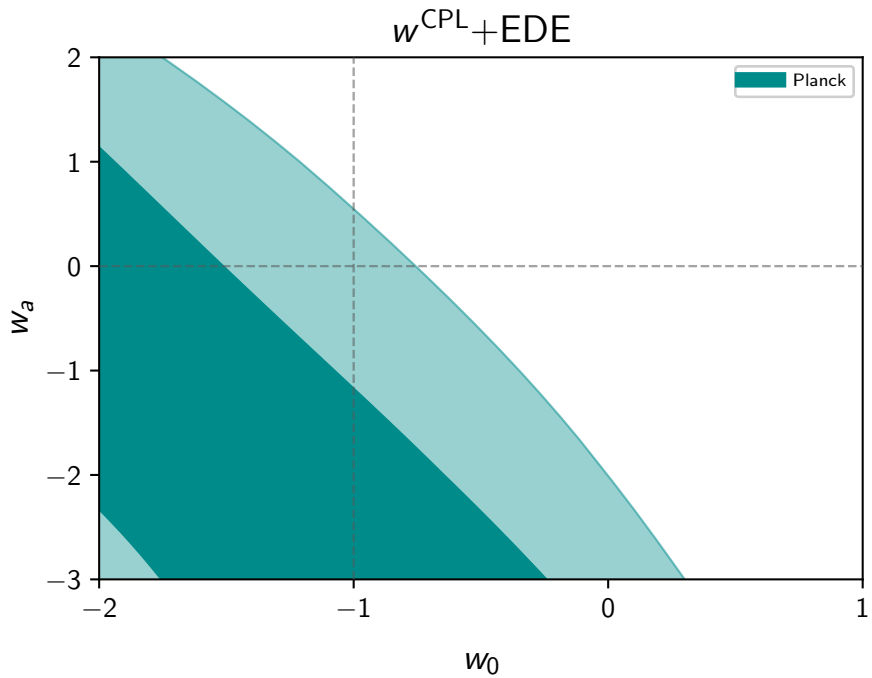
Dong & Park 2026 ApJ 998 66, arXiv: 2510.24089

Outline

Constraints from high-z probe

Planck: PR4(TTTEEE+lensing)

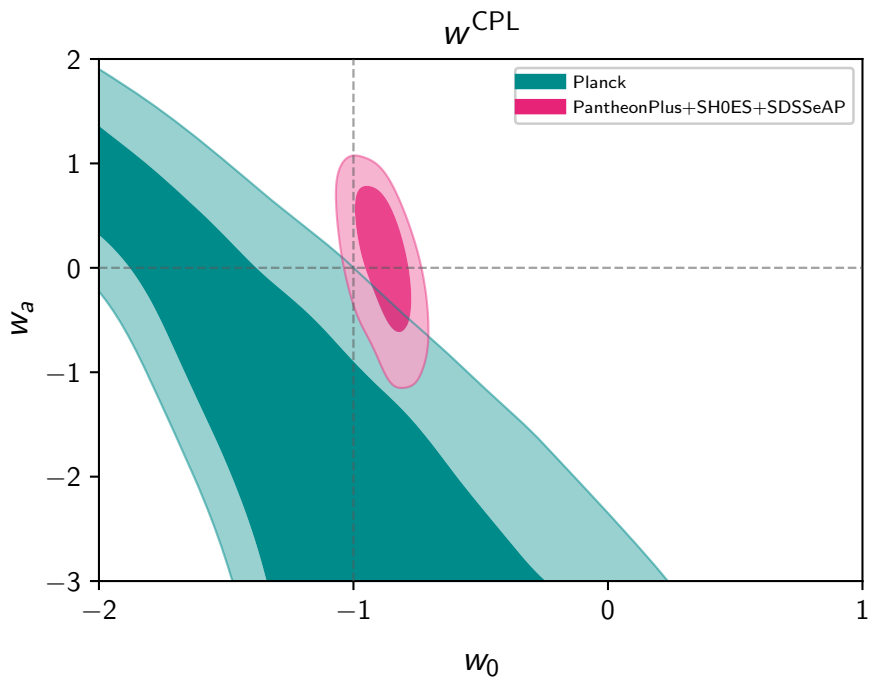


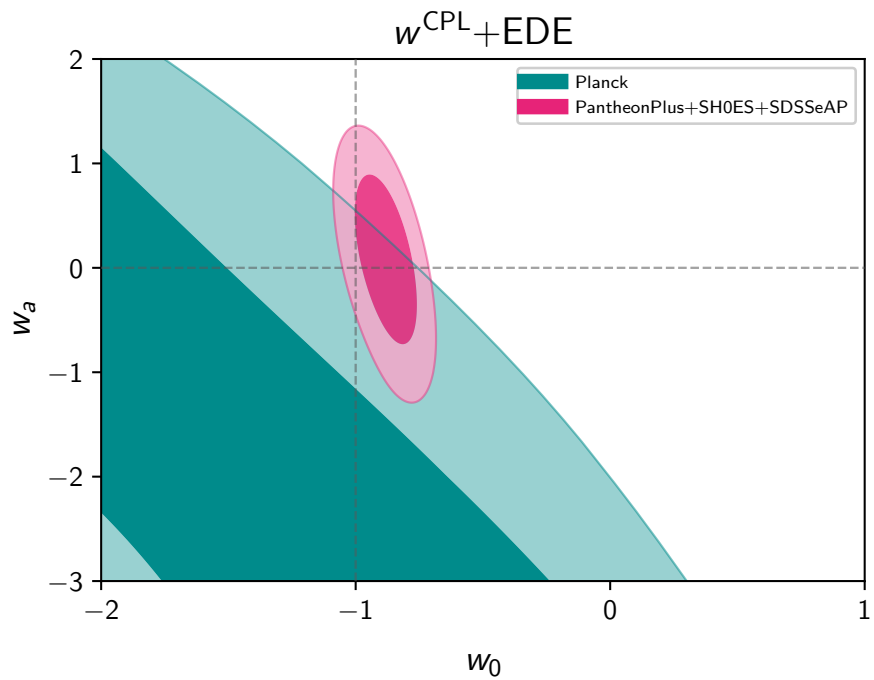


Unconstrained from CMB alone

Constraints from low-z probes

PantheonPlus+SH0ES+SDSS-eAP

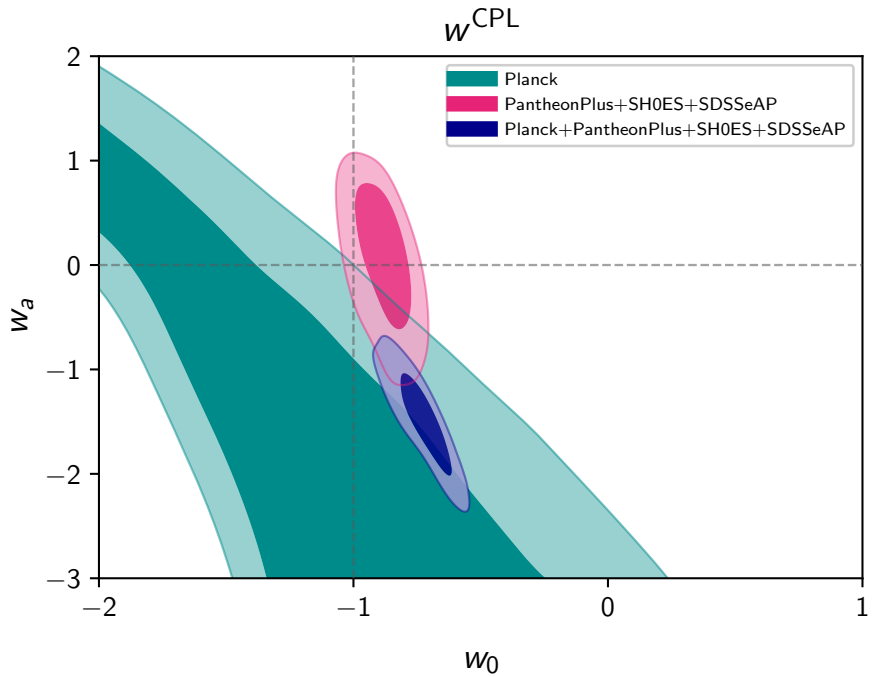




- $w^{\rm CPL}$: Constraints from low-z probes are consistent with ΛCDM or weakly dynamical DE; Dong & Park 2026 ApJ 998 66, arXiv: 2510.24089
- $w^{\rm CPL}$+EDE: EDE unconstrained by low-z data (no late-time imprint)

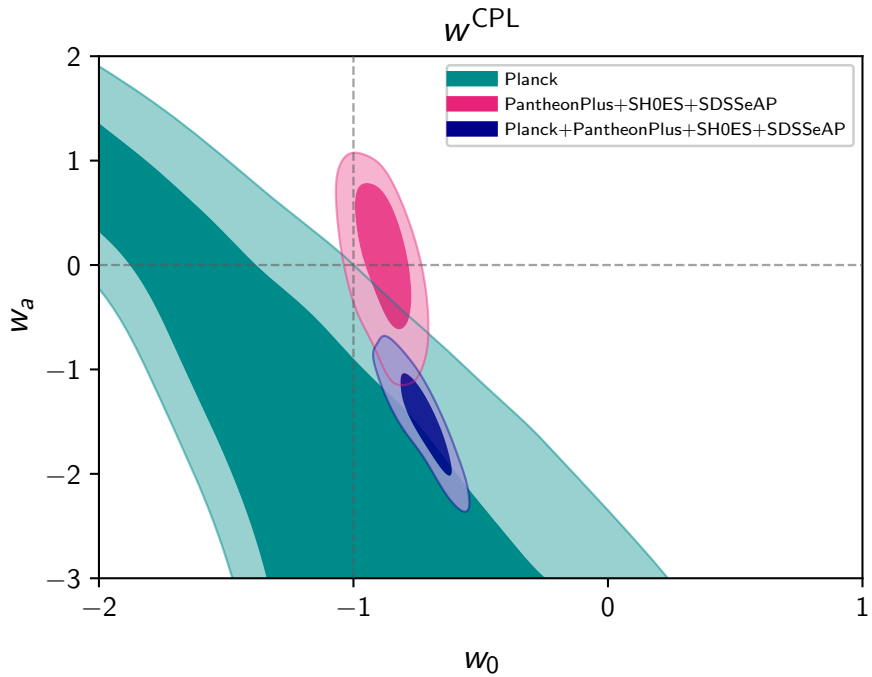
Constraints from high- & low-z probes

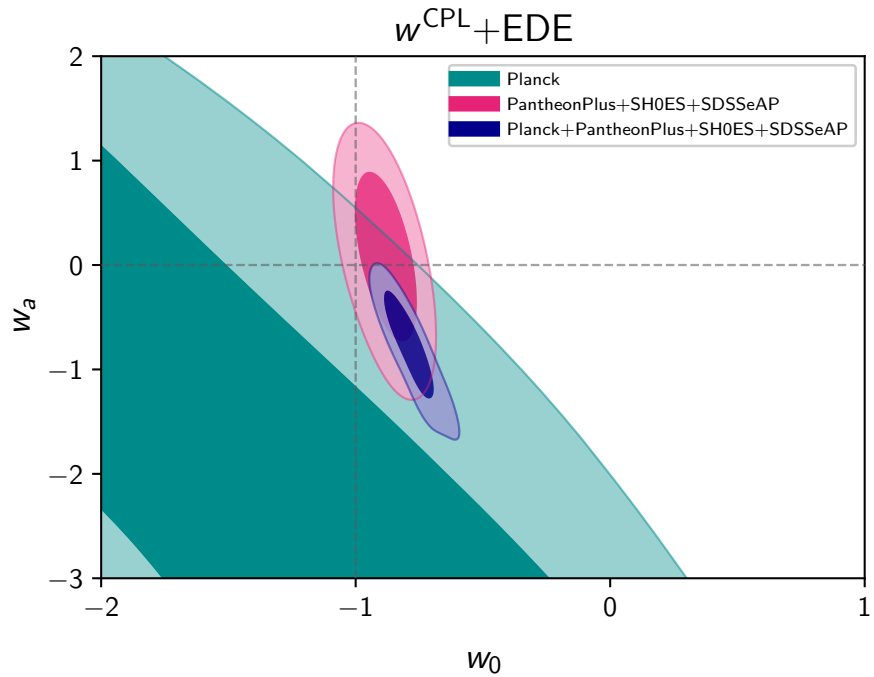
Planck+PantheonPlus+SH0ES+SDSS-eAP



Constraints from high- & low-z probes

Planck+PantheonPlus+SH0ES+SDSS-eAP

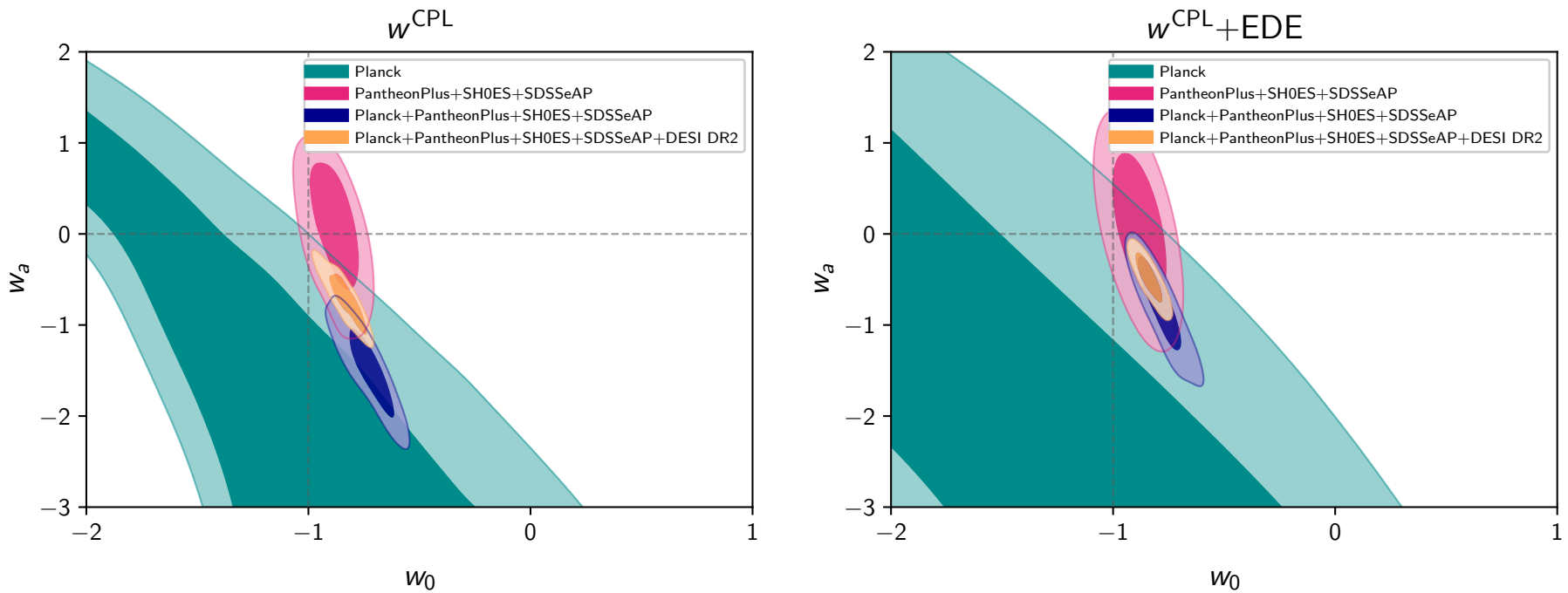




- Hints of dynamical DE become stronger ONLY when CMB is added!
- Addition of EDE reduces the tension with ΛCDM model; EDE raises H_0, lowers r_d

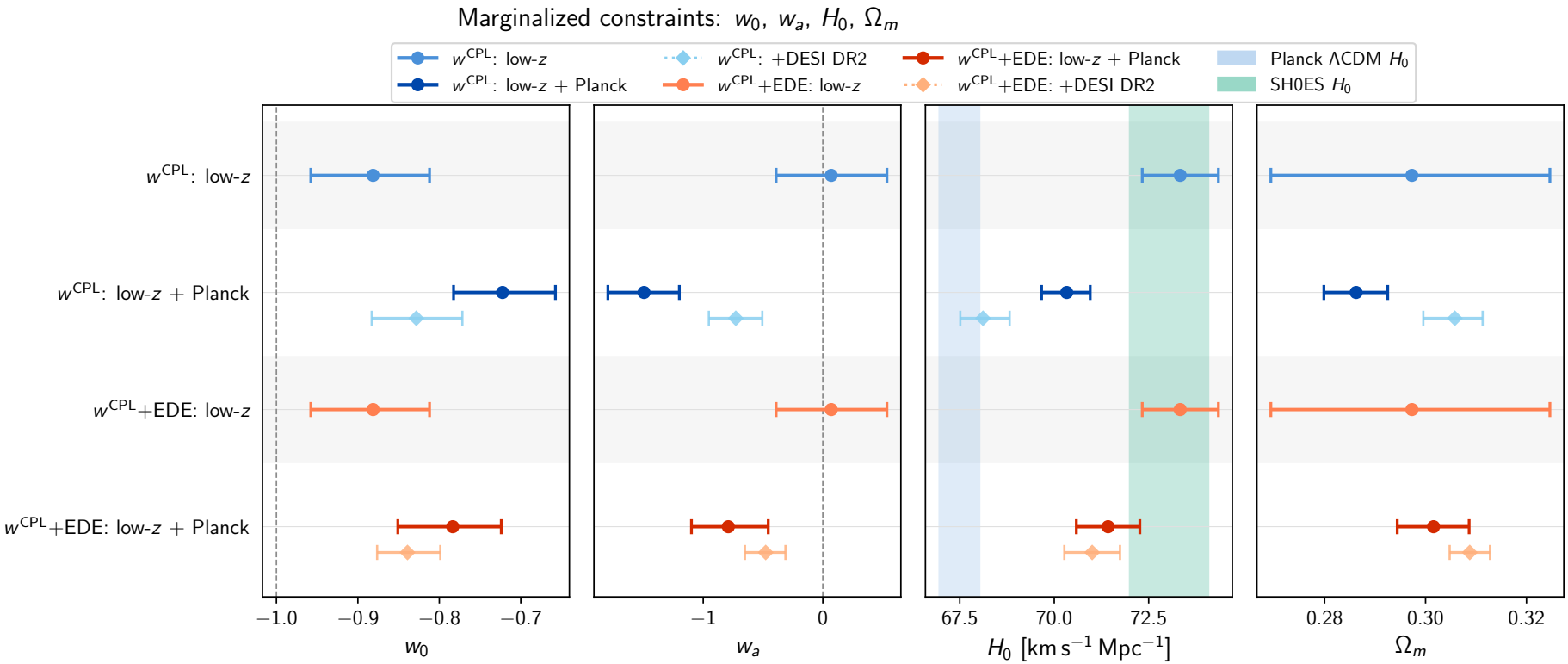
Constraints from high- & low-z probes

Planck+PantheonPlus+SH0ES+SDSS-eAP+DESI BAO

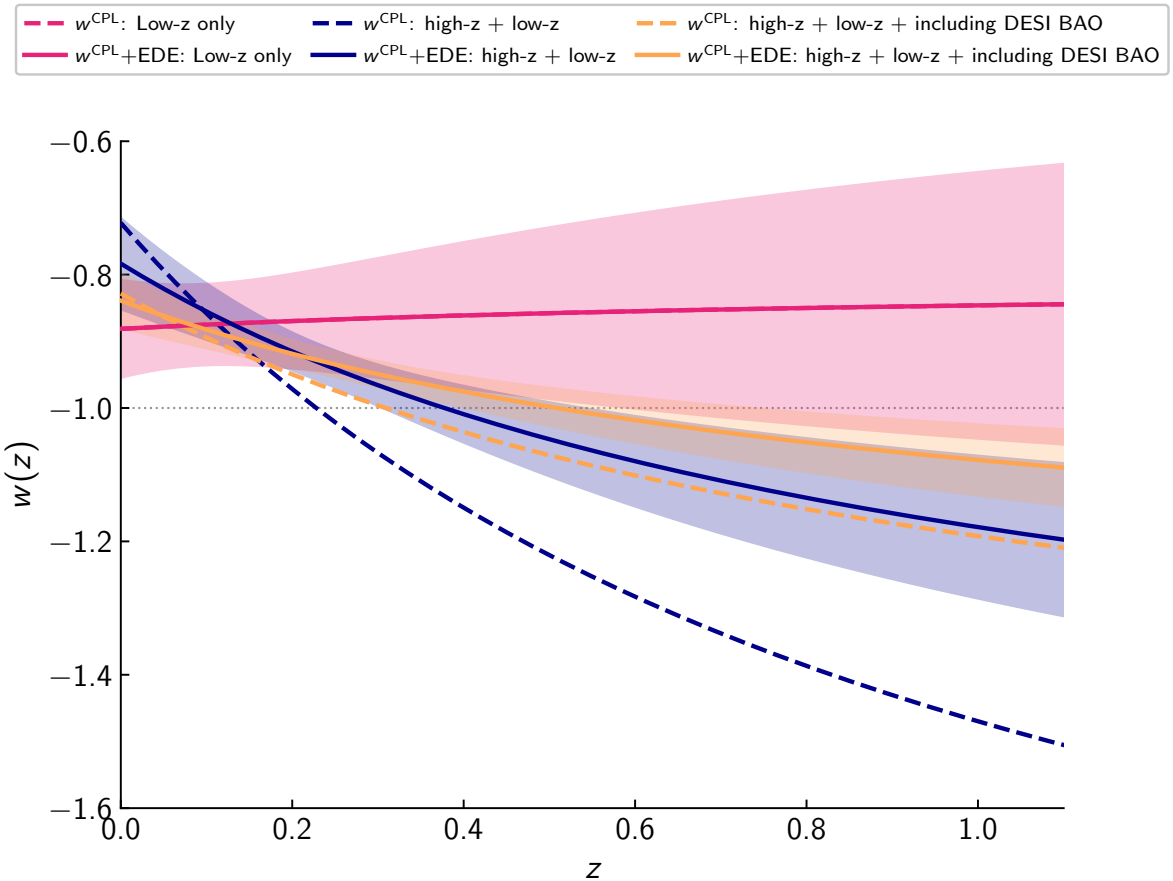


Effects of DESI BAO - contour shifts only mildly for EDE case $\Rightarrow$ low-z + CMB result is stable

Results


Marginalized constraints: w_0, w_a, H_0, Ω_m
$w^{\rm CPL}$: low-z
$w^{\rm CPL}$: low-z + Planck
$w^{\rm CPL}$: +DESI DR2
$w^{\rm CPL}$+EDE: low-z
$w^{\rm CPL}$+EDE: low-z + Planck
$w^{\rm CPL}$+EDE: +DESI DR2
Planck ΛCDM H_0
SH0ES H_0
$w^{\rm CPL}$: low-z
$w^{\rm CPL}$: low-z + Planck
$w^{\rm CPL}$+EDE: low-z
$w^{\rm CPL}$+EDE: low-z + Planck
−1.0
−0.9
−0.8
−0.7
w_0
−1
0
w_a
67.5
70.0
72.5
H_0 [km s^{-1} Mpc^{-1}]
0.28
0.30
0.32
Ω_m

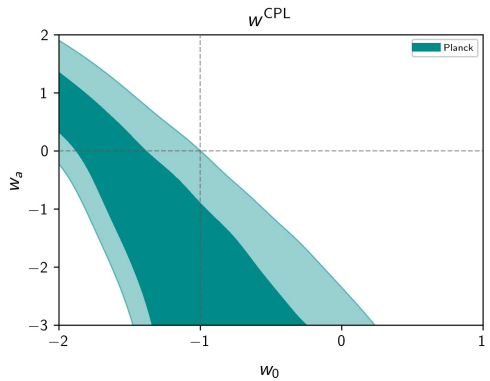
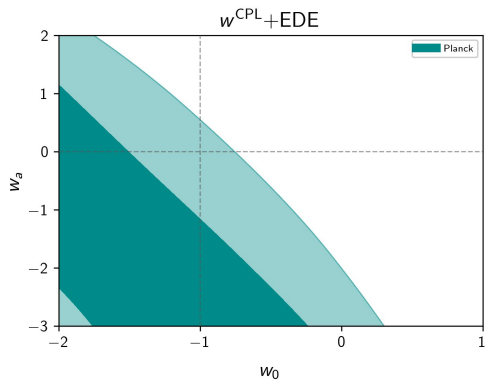
Evolution w(z)

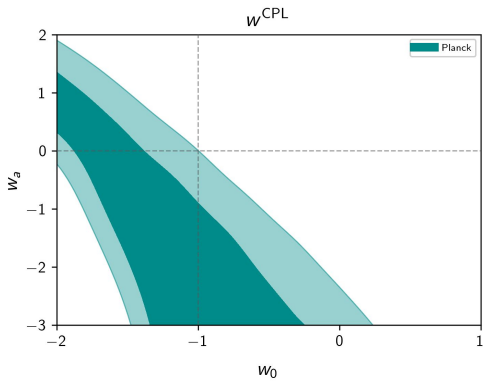
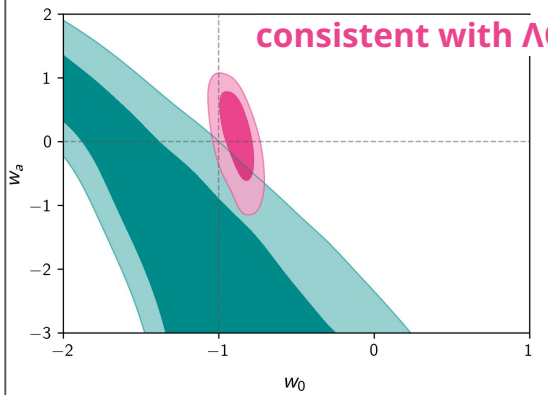
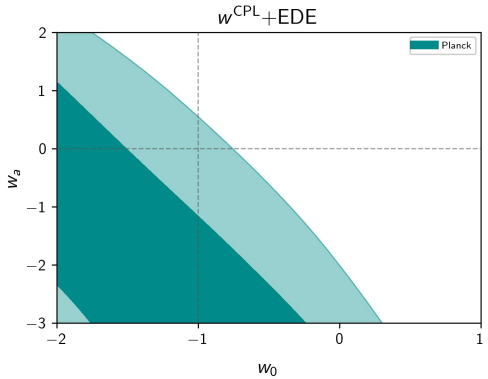
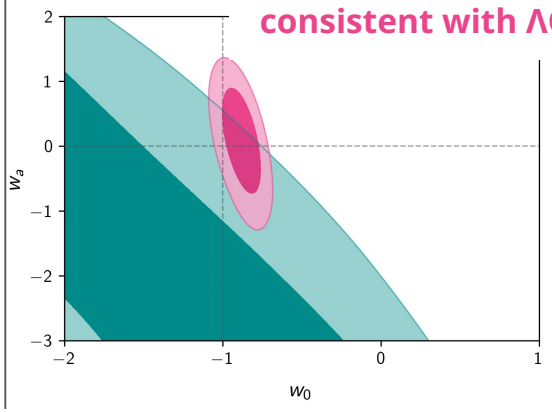


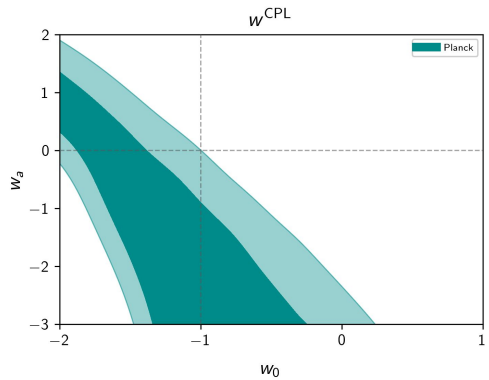
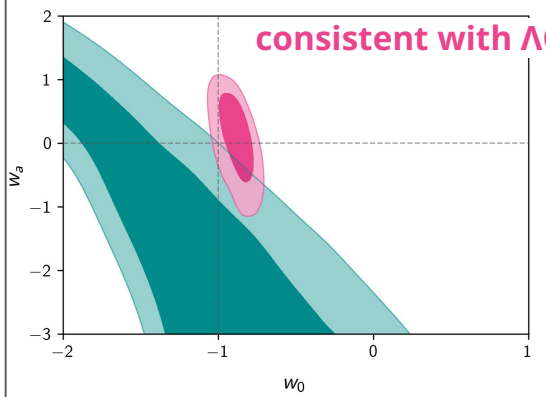
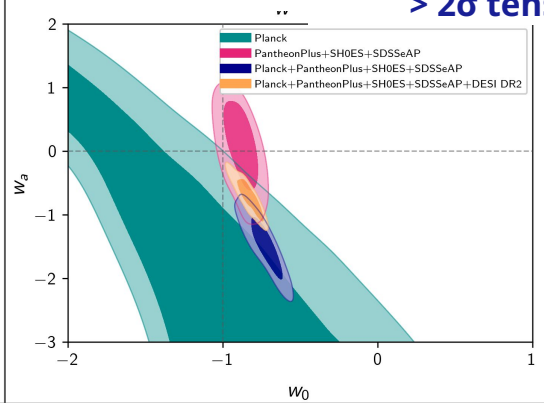
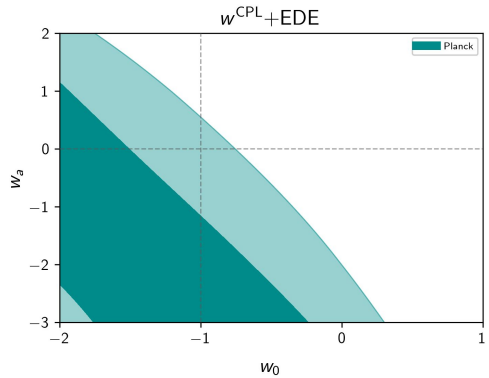
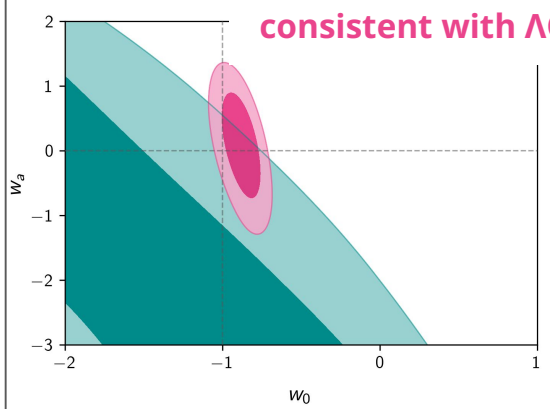
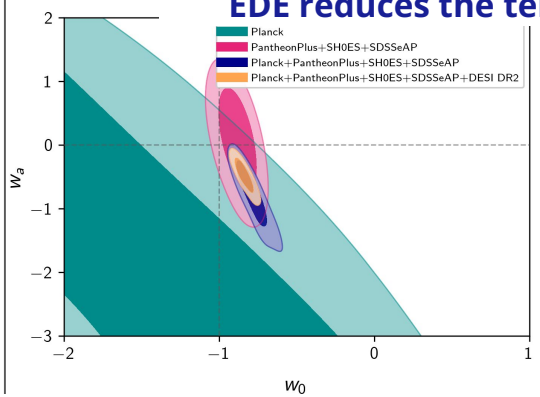
- Low-z only: no crossing of $w = -1$ at $z < 0.7$ (thawing-like); crossing appears only once CMB is added

Contents

	High-z probes	Low-z probes	Low-z + high-z probes
$w^{\rm CPL}$ models			
$w^{\rm CPL}$+ EDE models			

	High-z probes	Low-z probes	Low-z + high-z probes
$w^{\rm CPL}$ models			
$w^{\rm CPL}$+ EDE models	**EDE unconstrained by CMB alone** 		

	High-z probes	Low-z probes	Low-z + high-z probes
$w^{\rm CPL}$ models		$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	
$w^{\rm CPL}$+ EDE models	EDE unconstrained by CMB alone 	$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	

	High-z probes	Low-z probes	Low-z + high-z probes
$w^{\rm CPL}$ models		$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	$(w_0, w_a) = (-0.722^{+0.075}_{-0.054}, -1.49^{+0.33}_{-0.27})$ > 2σ tension 
$w^{\rm CPL}$+ EDE models	EDE unconstrained by CMB alone 	$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	$(w_0, w_a) = (-0.784^{+0.065}_{-0.074}, -0.79^{+0.41}_{-0.30})$ EDE reduces the tension 

Take-away points

- The evolving-DE signal is **sensitive to the high-z CMB data**:
  - Low-z alone (eAP + SN, no CMB): consistent with ΛCDM, $(w_0, w_a) = (-0.88, +0.07)$
  - Only with CMB does the tension appear: $(w_0, w_a) = (-0.72, -1.49)$, $> 2\sigma$
- The r_d-independent eAP anchor is consistent with ΛCDM and fits the CMB-driven dynamical solution poorly.
- **Early dark energy partially absorbs the pull:** $w_a : -1.49 \to -0.79$, and eAP consistency improves ($\chi^2_{\rm eAP} \to 5.5$) — but ΛCDM is *not* recovered
- Extended AP applied directly to DESI DR2 will give additional information
- The possibility of unified early+late scalar-field models will be explored.

Thank You